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PG1541+650: A new ZZ Ceti white dwarf*

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Abstract. We report the discovery of a new pulsating DA white dwarf, or ZZ Ceti, from the list of the Palomar-Green survey, rediscovered in the ongoing Hamburg Quasar survey (HQS). PG1541+650 is one of the ZZ Ceti candidates listed in the analysis of 80 DA white dwarfs from the HQS. With an effective temperature of 12000 K, for a surface gravity log$g$=7.79, it lies in the ZZ Ceti instability strip. It is indeed a ZZ Ceti star of large amplitude with at least three frequencies: the main mode has a frequency of 1.450 mHz (689 s period) with a relative amplitude of 0.045, with the other modes at 1.773 mHz (564 s period) and at 1.312 mHz (757 s) having smaller relative amplitudes of 0.015 and 0.014 respectively. The first harmonics of the dominant mode is seen at 2.911 mHz. According to its atmospheric parameters, PG1541+650 is the lowest mass recorded ZZ Ceti (0.5$M_\odot$) and should be close to the instability strip blue edge corresponding to its mass. If it is so, its rather long periods and large amplitudes do not fit with the general period-temperature and/or amplitude-temperature correlations.

Key words: stars: white dwarfs

1. Introduction

Asteroseismology offers a unique opportunity to infer the internal structure of stars. As far as the white dwarf stars are concerned, they are the end products of the evolution of most stars in the galaxy. Accordingly, they contain potential information regarding the previous phases of evolution, including some stages about which very little is sufficiently known to be safely included in stellar evolution computations, for instance: the mass loss rates on the AGB and post-AGB phases and the evolution of the angular momentum. It is why understanding the internal structure of white dwarfs may help constraining various scenarii suggested for these uncertain evolutionary phases.

Getting a better knowledge of the internal structure of white dwarfs has also a direct impact on other astrophysical fields. For instance, the age of the galactic disk in the solar neighborhood may be derived from the age of the oldest white dwarfs by fitting the observed white dwarf luminosity function with theoretical evolutionary cooling sequence. This method, first suggested by Winget et al. (1987) suffers from two main uncertainties: 1) the determination of the outer hydrogen layer mass, which, due to the high hydrogen opacity, controls the cooling time scale, and 2) the estimate of the efficiency of the C-O crystallization process in the degenerate core.

In principle, asteroseismology could give constraints on the total mass of the white dwarfs, on the mass of the outer layers, and on the chemical composition of the degenerate core via measurements of the period spacing, of the mode trapping and of the period rate of change ($\dot{P}$), respectively. In fact, some very efficient selection mechanism, still to be unambiguously identified, dramatically reduces the number of nonradial modes seen in most ZZ Ceti stars, making impossible to derive the total mass and the mass of the hydrogen layer from asteroseismological data alone. Other observational constraints must be used, to take advantage of the tools provided by asteroseismology.

Pulsating white dwarfs are found along the cooling sequence in three distinct instability strips: the pulsating PG1159 stars or GW Vir, for 150000 K$\geq T_e \geq$ 75000K, the pulsating DB white dwarfs (DBV), for 30000 K$\geq T_e \geq$ 22000 K, and the pulsating DA white dwarfs (DAV) or ZZ Ceti stars, for 12400 K$\geq T_e \geq$ 11200 K. Each of these instability strips occurs when the main chemical constituent in the envelope recombines. In the PG1159 stars the partial ionization of C and O has been suggested to produce the instability (Starrfield et al. 1983, 1984; Stanghellini et al. 1991; Bradley and Dziembowski 1996; Saio 1996). In the DB white dwarfs the He recombination triggers the pulsations (Winget et al. 1982b). For the DA white dwarfs, early work suggested the κ-mechanism associated to the H partial ionization as the driving mechanism (Dolez and Vauclair 1981; Winget et al. 1982a). Following the work of Brickhill (1983, 1991a, 1991b) it is now recognized that the convection plays a dominant role in the driving of the pulsation modes in ZZ Ceti stars (Gautschy et al. 1996; Goldreich and Wu 1999; Wu and Goldreich 1999).

Since the discovery of the first pulsating DA white dwarf HL Tau 76 by Landolt (1968), continuing search for pulsating white dwarfs have resulted in the discovery of the two other classes of pulsators: the PG1159 stars with the discovery of PG1159-035 (McGraw et al. 1979) and the pulsating DB with

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* Based on observations obtained at the Telescope Bernard Lyot of the Pic du Midi Observatory and at the Haute Provence Observatory, both operated by the Institut des Sciences de l'Univers of the CNRS

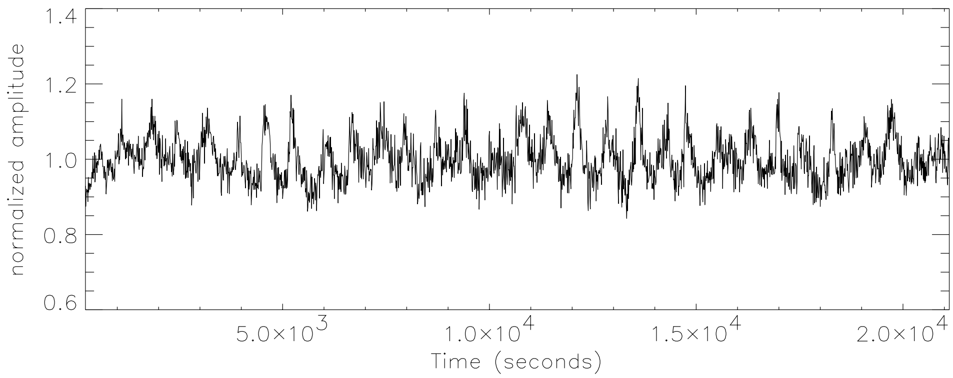

Fig. 1. Normalized light curve of PG1541+650 obtained on May 15th, 1999 at the 1.93 m telescope of the Haute Provence Observatory. The relative amplitude is plotted versus the time in seconds

the discovery of GD358 (Winget et al. 1982b). At the present date, 5 pulsating PG1159 stars are known, including the pulsating "hybrid" PG1159 HS2324+3944, 8 DBV and 28 DAV. The list of pulsating white dwarfs may be found in the proceedings of the successive WET workshops, regularly updated by Bradley (1998) with a summary of their properties and further references. Our knowledge on the structure and evolution of these late stages of stellar evolution based on asteroseismology still relies on a very small number of stars. Increasing the number of known variable white dwarfs is an important issue as it improves our understanding of their properties on a statistically more significant basis. This paper reports on our continuing effort to search for new pulsating white dwarfs with the discovery of one new ZZ Ceti star: PG1541+650.

2. Observations

PG1541+650 is listed in the Palomar-Green survey (Green et al. 1986) as a DA5 type white dwarf with no more details. It was also found in the more recent Hamburg Quasar survey (HQS, Hagen et al. 1995). Homeier et al. (1998) have analysed spectroscopically eighty DA white dwarfs found in the course of the HQS for atmospheric parameters determination. Among this sample some stars have the right atmospheric parameters to be ZZ Ceti candidates. We have undertaken fast photometry observations of these ZZ Ceti candidates. We have reported elsewhere the discovery of the ZZ Ceti HS0507+0435 from this list (Jordan et al. 1998). With an effective temperature of T_e=12000 K for a surface gravity log$g$=7.79, PG1541+650 lies inside the instability strip as defined by Bergeron et al. (1995).

We used the Chevreton 3-channel photometer equipped with blue sensitive Hamamatsu (R647-04) photomultipliers without filters. The three channels measure simultaneously the variable candidate, a comparison star and the sky background respectively. The chosen integration time was 1 s.

As PG1541+650 is a rather faint star (B=15.7), we performed the observations on 2m class telescopes. The Chevreton's photometer was first attached to the Pic du Midi 2m telescope. We obtained a 3200s run on August 23, 1998. The run was long enough to reveal the large amplitude pulsation of PG1541+650 and it covered approximately 5 pulsation cycles, indicating a quasi-period close to 11 min. We were not able to repeat the observation to confirm the variability, due to the poor observing conditions on the followings nights. We have reobserved PG1541+650 last May 1999 at the 1.93 m telescope of the Haute Provence Observatory, during two consecutive nights, on May 14th and 15th. We obtained a ≈9000 s run on May 14th, and a much longer high quality run of 20900 s on May 15th.

3. Preliminary analysis

Fig. 1 shows the May 15th 1999 normalized light curve. The corresponding amplitude Fourier transform is shown in Fig. 2.

The noise level above 1 mHz is ≈4-5 mmag. The FT is clearly dominated by a single peak at 1.458 mHz (period of 686 s) with a relative amplitude of 0.045. A second peak is seen at 1.775 mHz (period of 563 s) with a relative amplitude of 0.015. A third peak at 1.320 mHz (period of 757 s) shows a similar relative amplitude of 0.014. The first harmonics of the dominant peak is also seen at 2.912 mHz with a 0.012 relative amplitude. The frequency resolution from this single night is 48 μHz. The data obtained on August 23th, 1998 and on May 14th, 1999 show the same large amplitude peak which is at 1.416 mHz and 1.463 mHz respectively, with a larger uncertainty due to the lower frequency resolution. The dominant peak has approximately maintained a constant amplitude since the discovery run. The second frequency is also present, within the uncertainty of the reduced resolution data at 1.877 mHz and 1.856 mHz respectively.

The fact that we got two consecutive night runs on May 14th and 15th, 1999 offers the opportunity to improve the resolution of the frequency determination. In spite of the short length of the May 14th run, sometimes interrupted by clouds, the addition of the two runs improves significantly the window function. To analyse the combined light curves, instead of applying directly the usual Fourier transform techniques, we used an autoregressive parametric model which allows us to predict the time series between the two runs, using the informations contained in the data. The method is described in Schwarzenberg-Czerny et al. (2000). It assumes that the current value of the signal depends on a given number of its past values plus a noise term. By using this characterization it is possible to generate an extrapolation of the signal over some prediction horizon (Weigend & Gershenfeld 1994).

Fig. 3 illustrates how this method compares with the usual Fourier transform techniques. For this purpose, the figure shows

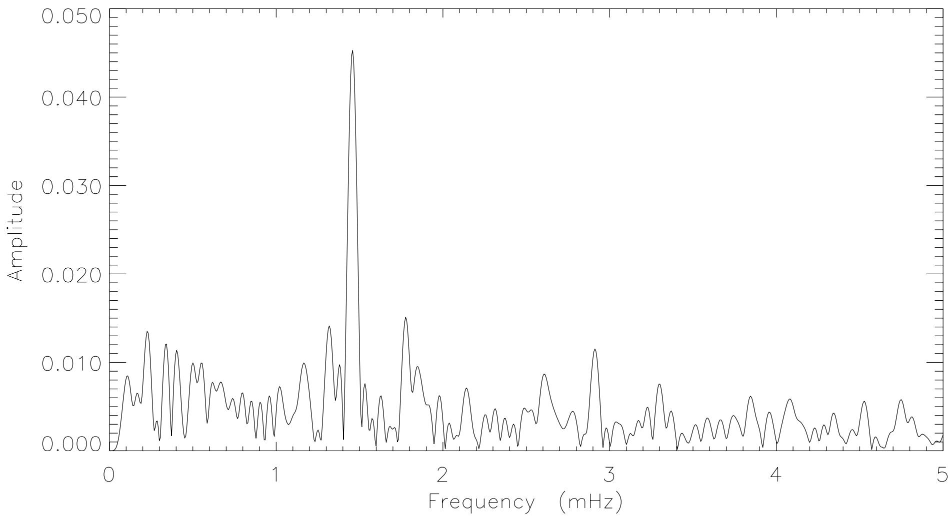

Fig. 2. Fourier spectrum, in amplitude, of the PG1541+650 light curve shown on Fig. 1. The amplitude is plotted as a function of the frequency in the range 0-5 mHz.

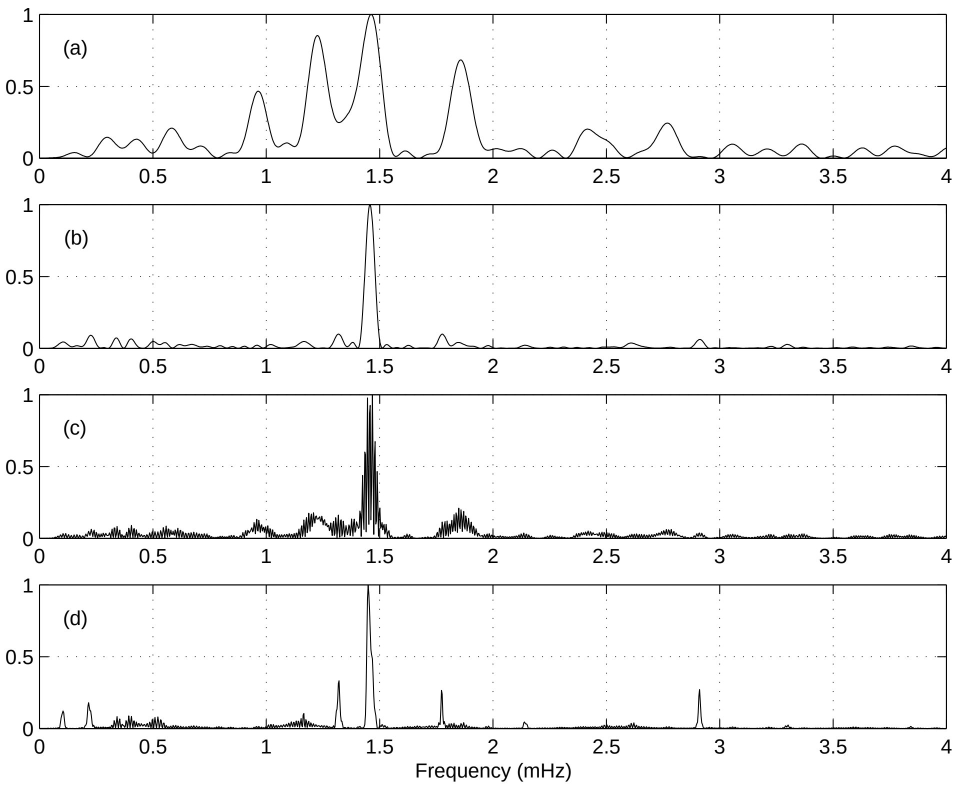

Fig. 3a – d. Power spectrum of PG1541+650, normalized to the power of the dominant peak at 1.45 mHz: **a** power spectrum of the May 14th, 1999 light curve; **b** power spectrum of the May 15th, 1999 light curve; **c** power spectrum of the combined light curves obtained through the usual Fourier Transform techniques; **d** power spectrum of the combined light curves obtained by using the auto-regressive parametric method.

various power spectra normalized to the power of the dominant frequency, in the frequency range 0-4 mHz. The part a of the figure shows the power spectrum of the May 14th light curve. It reflects the poor quality of the data and the short length of the run. Nevertheless, the large amplitude mode at 1.45 mHz is well defined. The part b shows the power spectrum of the May 15th light curve. It is the same as Fig. 2, except that the normalized power is plotted instead of the amplitude. Part c illustrates the power spectrum of the combined light curves using the usual Fourier transform techniques which assumes the signal to be equal to zero between the two runs. The final part d shows the power spectrum obtained by using the auto-regressive parametric model. The method allows to get rid of the aliases and the frequency resolution is the one expected for a run having a total length equals to the time elapsed between the beginning of the first run and the end of the second one, which in our case is ≈ 9.5 μHz, a factor of 5 improvement compared to the resolution obtained from the single May 15th run. The improved frequencies determination of the 4 identified peaks are 1.321 mHz (period 757 s), 1.450 mHz (689 s), 1.773 mHz (period 564 s) and the harmonics at 2.911 mHz. In addition, a fifth peak barely seen in the Fourier spectrum of the May 15th light curve, seems to emerge more convincingly at 2.14 mHz (period $\approx$467 s) in a region of the power spectrum where the noise level is lower.

4. Conclusions

We have reported the discovery of the 29th pulsating DA white dwarf PG1541+650. It is another multi-periodic ZZ Ceti star with at least three (may be four) modes detected, plus the first harmonics of the largest amplitude one. With the atmospheric parameters derived by Homeier et al. (1998) T_e=12000 K $\pm$70K, log g= 7.79± 0.04, it is presently the lower mass ZZ Ceti with M = 0.5 $M_\odot$. According to the theoretical calculation of the instability strip blue edge by Bradley & Winget (1994), this places the star very close to the blue edge corresponding to its presumed mass, which they predict at 12270 K. The star does not follow the general trend according to which the ZZ Ceti entering the instability strip tend to have short periods and low amplitudes, and then increase both their periods and amplitudes as they cross the instability strip (see for instance Clemens 1993). Looking at the list of ZZ Ceti atmospheric parameters determined by Bergeron et al. (1995), the star with atmospheric parameters the closest to those of PG1541+650 is G238-53, with T_e=11890 K and log$g$=7.91. G238-53 has a main period of 206 s with an amplitude $\leq$0.009 (Fontaine & Wesemael 1984), to be compared to the main period of 689 s and to the relative amplitude of 0.045 in PG1541+650. It should be noted, however, that the parameter determination by Homeier et al. (1998) rests on optical spectra alone. It is well established (e.g. Koester and Vauclair 1997) that systematic errors in this case can be much larger than the statistical errors deduced from a χ^2 analysis. If taken at face value, the PG1541+650 atmospheric parameters suggest that the period-temperature and the amplitude-period (or equivalently the amplitude-temperature) correlations found for the ZZ Ceti in average, could be not true for the low mass ZZ Ceti stars, or that the correlations, if they exist, should have a much steeper slope, due to the narrowing instability strip as the mass decreases. PG1541+650 is certainly an interesting ZZ Ceti to follow up to understand its particular behaviour.

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